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ABSTRACT

This issue of Exploratorium Magazine focuses on the topic of motion. Contents include: (1) "First Word" (Zach Tobias); (2) "Cosmic Collisions" (Robert Irion); (3) "The Mobile Cell" (Karen E. Kalumuck); (4) "The Paths of Paths" (Steven Vogel); (5) "Fragments" (Pearl Tesler); (6) "Moving Pictures" (Amy Snyder); (7) "Plants on the Go" (Katharine Miller); (8) "Try This! Plant Tropisms" (Karen E. Kalumuck); (9) "Motion in the Eye of the Beholder" (Hugh McDonald); (10) "That Queasy Feeling: Why Reading and Riding Don't Mix" (Lauren McLean Ayer); and (11) "The Ultimate Speed Limit" (Paul Doherty). (YDS)

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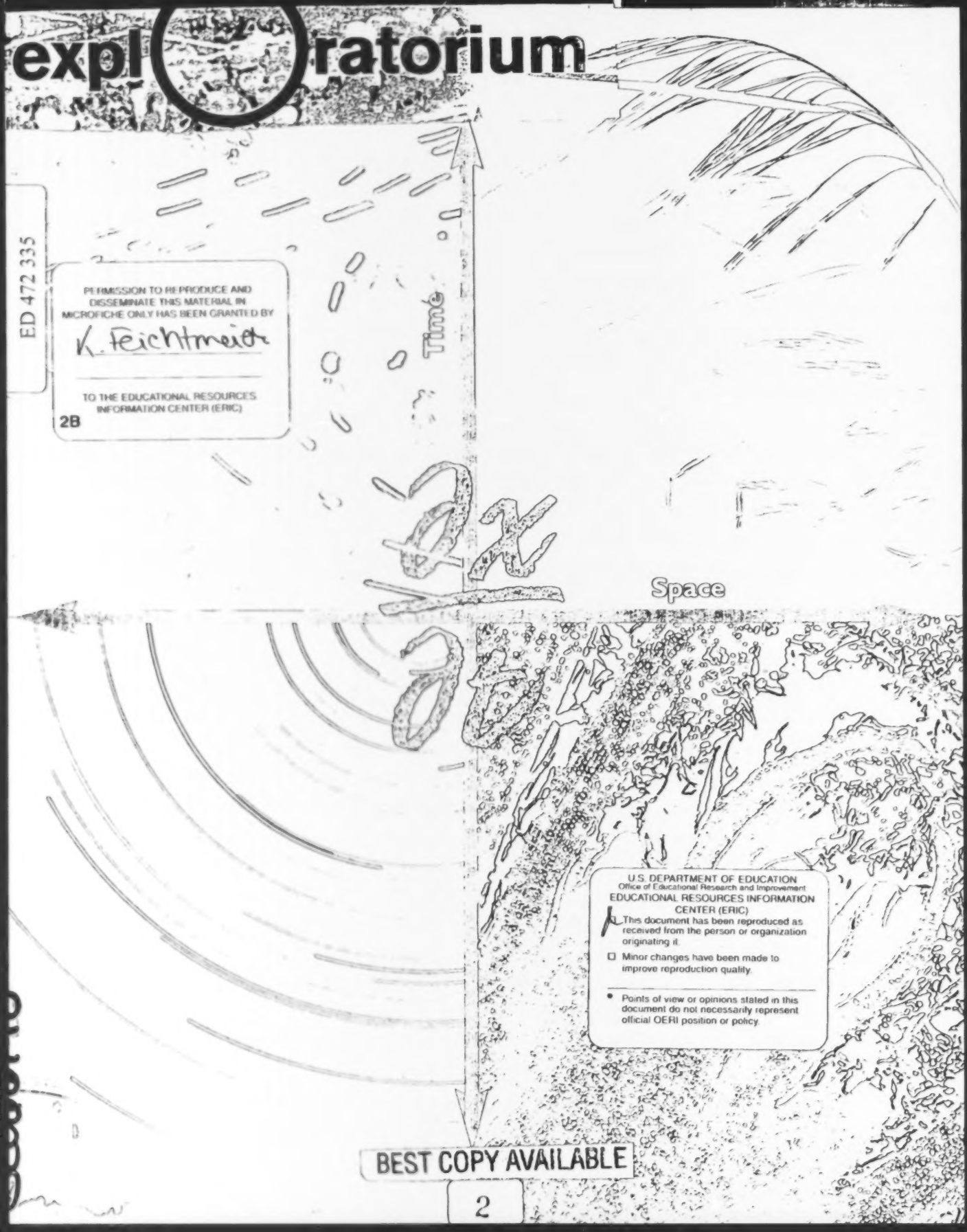

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The Exploratorium Magazine is produced quarterly by the Exploratorium, a museum of science, art, and human perception. The magazine communicates ideas that exhibits can't easily demonstrate, extending the museum beyond its physical walls. Each issue takes an in-depth look at a single topic, explaining the underlying science of the everyday world.

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From the Director

Dear Friends,

I'm pleased to announce the publication of our latest book, *Square Wheels and Other Easy-to-Build, Hands-On Science Activities* by Don Rathjen, Paul Doherty, and the Exploratorium Teacher Institute. For over two decades, the Exploratorium has developed numerous books, posters, and other "learning tools" that extend the museum's philosophy of interactive education to a worldwide audience. We currently have more than thirty of these titles in print, ranging from classroom activity books, such as *Square Wheels*, to beautiful art photography books, such as *Traces of Time*. We produce material for teachers, families with children, and exhibit designers, as well as general-interest materials for adults. This year, we're expanding our work to develop materials for after-school programs.

To produce the highest quality publications for each of these audiences, the Exploratorium Learning Tools division coordinates a rigorous development process, similar to the process we use for creating new exhibits. Staff members throughout the museum generate ideas for new publications, often as a result of their work on other museum or education programs. Once an idea has been vetted and approved, we assemble a team of staff members and outside collaborators to help with the project. Exploratorium senior scientists and educators check the science content for accuracy and clarity of presentation. For activity books, teachers, students, and families volunteer to try the activities and let us know what works and what doesn't. Our designers and editors continually rework the material based on these reviews. In many cases, we work with a specialty publisher who helps us better understand the interests of a particular audience. When the publication is released, we know that it has been thoroughly tested.

Much like our exhibits, which have been replicated for museums worldwide, our publications are widely acclaimed for making learning enjoyable, and they have helped establish the Exploratorium as an innovative leader in science education. Importantly, their popularity generates revenue that supports our continued development of educational materials.

The next time you drop in at the Exploratorium Store or visit our Web site, I encourage you to browse through the variety of Exploratorium publications. Whatever your interests, I'm sure you'll discover a book that's both delightful and informative.

Yours,

Goéry Delacôte
Executive Director

BE CAREFUL! The experiments in this publication were designed with safety and success in mind. But even the simplest activity or the most common materials can be harmful when mishandled or misused. Use common sense whenever you're exploring or experimenting.

Cover: Images clockwise from top left show a bicycle race, grass blowing in the wind, growth of an ash bud, and the apparent motions of celestial bodies around the earth. We can gain understanding of all these seemingly disparate motions from the mathematical expression $\partial x/\partial t$, where ∂x represents a change in spatial position and ∂t is an interval of time.

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First Word

by Zach Tobias

The best dance partner I ever had was Manuel, a man I worked with in a cabinet shop many summers ago.

The work we did was mass production at its most tedious. But somehow, and without ever mentioning it to one another, the two of us found a kind of sublime grace in the steps we did together each day.

The dance started with our hauling four-by-eight-foot sheets of particle board to a wall-mounted saw. The boards were big, flat, and heavy—extremely awkward things to carry. To move them with any semblance of dexterity (and to save our fingers), we had to coordinate perfectly, sensing each other's direction and making our own movements perfectly clear.

Once a board was on the saw, the dance became more complex. Manuel, who was clearly the leader, would make the cuts, walking the saw blade smoothly down the length of the board. It was up to me to reposition the now smaller pieces for the next series of cuts. The key was not to make him wait, but to get the next piece in place right at the moment when Manuel was ready to move the blade again.

When it all fell into place, cutting those boards became an intricate cycle of lifting, sliding, sawing, and stacking. Sometimes, a stack of ten four-by-eights would seem to cut itself in one continuous motion. Other times, when Manuel and I weren't in the groove, we would become entangled in our own jerky, inefficient, and sometimes painful movements, like two villains caught in Spiderman's web.

All kinds of everyday activities offer the opportunity to achieve beauty through movement, even activities that some would find distasteful. Zhuangzi, a Chinese Taoist in the fourth century B.C., told the story of a master butcher who wielded his cleaver with a dancelike motion, carving carcasses with incredible ease. How, the butcher was asked, did he attain such skill?

"I meet the ox with my spirit rather than look at it with my eyes," he explained. "In accord with the natural grain, I slice at the great crevices, lead the blade through the great cavities. . . . Whenever I come to a complicated spot and see that it will be difficult to handle, I cautiously restrain myself, focus my vision, and slow my motion. With an imperceptible movement of the cleaver, plop! and the flesh is already separated, like a clump of earth collapsing to the ground."

For Zhuangzi, skilled craftspeople provided a model for how we could all lead our lives. Having honed their skills through years of practice, they could act automatically, achieving a deeply natural flow.

But it's not only people with special skills who achieve physical grace. Even the simplest actions involve a complex choreography between nerves, muscles, and mind. Every time we carry a load—say, a bag of groceries—our shoulders must make constant, tiny adjustments to keep us from falling, like a tightrope walker balancing his pole. Every time we reach to grab a telephone, muscles from our shoulders to the tips of our fingers simultaneously contract and relax, our bones gliding effortlessly at the joints.

It was once believed that the brain pumped an amorphous spirit into the body to make it move. We now have a clearer picture of how nerves carry electrical impulses to the muscles, making motion possible. But there remains something mysterious about human movement, something that science may never be able to fully explain. Because moving isn't just a physical act: It is (usually, at least) also an act of the will.

In his book *Awakenings*, neurologist Oliver Sacks describes patients who remain frozen and silent for days—and sometimes years—on end. Parkinson's disease has robbed them of something few of us realize we have. The problem is not that they are physically unable to move; they are not paralyzed. Rather, they have lost the internal metronome that makes human motion possible.

One patient is able to walk up stairs with no trouble, but freezes once there are no more steps to establish a rhythm to her walking. Others get up and dance when music is played, or catch a ball when someone throws it to them, even though their bodies are normally locked in one position. "I can do nothing alone," explains one patient, who says she has been "unmusicked" by the disease. "I can do anything with—with music or people to help me. I cannot initiate, but I can fully share. You 'normals,' you are full of 'go,' and when you are with me I can partake of all this. The moment you go away I am nothing again."

Tragic as the stories of Sacks's patients are, they make us aware of a gift that is fundamental to our lives. It's true: People are full of "go," a universal quality that shows itself uniquely in each of us. The way we move, after all, is as individual as our fingerprints. I remember being on a walk late at night and seeing a person disappear around a corner. Although I barely caught a glimpse of him, I immediately knew it was an old acquaintance I hadn't seen in years. I could easily have forgotten his face, but I could never forget his walk.

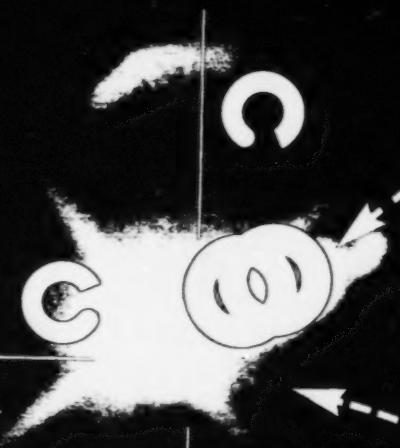
In a sense, we are all dancers, our movements expressing our innermost being. Perhaps it was this that the choreographer Merce Cunningham, who shocked audiences with his avant-garde dances in the 1950s, was best able to see. Cunningham usually choreographed and rehearsed his pieces without accompaniment, only adding music once they were performed. Instead of adhering to traditional dance steps, he often drew his inspiration from the movements of everyday life, like children skipping, or the act of putting on a sweater.

Maybe Cunningham was right to leave the line between dance and life blurry. So much music comes from the motion of everyday life, whether it's the songs that workers sing as they swing their tools, or the countless folk tunes inspired by the rocking of trains. And who's to say that the most mundane actions aren't a form of art? From pizza chefs tossing disks of dough to office workers sprinting for their trains, we all dance our way through life, with or without a sound track. ➤

all dancers

COSMIC COLLISIONS

by Robert Irion



Everything moves. This law of nature is easy to see on a spring day as the wind sways branches outside our windows and the petals of a rose unfurl to the Sun. A glance at the night sky seems to reveal a gently moving cosmos as well, with planets wandering among the stars and constellations that rise and set as Earth spins ceaselessly.

However, that graceful sky is a mirage. Not only do most objects in the universe move with more speed than anything on Earth can muster, but they crash with unimaginable violence. Indeed, near misses and head-on collisions dictate the shapes of most galaxies, the structure of our solar system, the appearances of planets, and—possibly—the very evolution of life.

Earth itself is no slowpoke. A person standing on the planet's equator whirls at a bit more than a thousand miles (1,600 km) per hour as Earth rotates on its axis once per day. That same traveler whips through space at nearly seventy thousand miles (112,000 km) per hour as Earth revolves around the Sun. We don't notice these motions because everything on Earth—including the atmosphere above us—moves together. Gravity prevents us from simply careening off into space. However, gravity also is the only force of nature that extends across cosmic distances. Its hidden tentacles can accelerate stars and entire galaxies to breathtaking speeds.

Astronomers learn about the consequences of continuous motion in the universe by studying the havoc it leaves behind, such as distorted galaxies and the scarred surfaces of rocky planets and moons. Earth is not immune to the action. Impact craters testify to asteroids that have slammed into our planet in the past, including one collision that probably eradicated the dinosaurs sixty-five million years ago.

Such major collisions happen rarely on human time scales. However, two events in the twentieth century reminded scientists of the ongoing hazard. In 1908, a small asteroid or comet exploded in the air over the Tunguska River in a remote part of western Siberia, flattening trees for dozens of miles in all directions. And in 1994, astronomers watched the pieces of a comet plunge into the atmosphere of Jupiter one after the other, raising titanic blast waves and creating dark marks far bigger than Earth. Planetary scientists Carolyn Shoemaker and the late Eugene Shoemaker noted that the event had other repercussions as well. "At the end of 'impact week,' our most important conclusion was a newfound appreciation that such impacts have happened on Earth in the past and could happen again, at any time, with devastating effects to civilization."

Our restless sun and rocky neighbors

To understand the risks posed by motion within the solar system, it helps to start with the fountainhead of activity in our neighborhood: the Sun. This nuclear furnace is a typical middle-aged star, yet its life is anything but sedate. The Sun spews an unrelenting barrage of high-energy particles into space, a literal "solar wind" through which the planets revolve. The particles are blobs of hydrogen, helium, and other elements from the Sun's surface, flung outward by magnetic fields that twist and snap like overstretched rubber bands. They stream through space at a million miles (1.6 million km) per hour, more than five thousand times faster than the gusts of the fiercest hurricanes on Earth.

When these tiny pieces of the Sun dive into the magnetic field that surrounds our planet, they set off shimmering curtains of aurorae near the North and South Poles. Particularly violent storms of activity on the Sun—unleashed by intense sunspots at the star's surface—propel the northern auroral lights to latitudes where residents of the lower forty-eight states can see them. Such storms also can spark electrical short-circuits in satellites, and their radiation is dangerous to any astronauts working outside of their shielded vessels.

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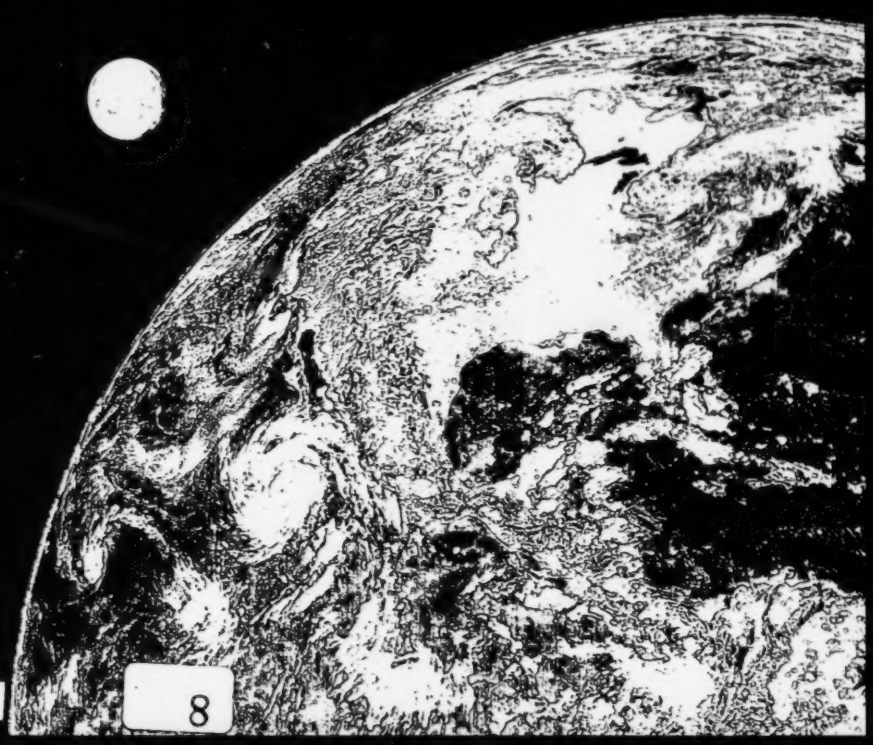
›nstant motions—and violent collisions—drive the fates of planets, galaxies, and the universe itself.

After the Sun sets, other bits of the solar system flash into view as meteors pierce the darkness. These streaks of light—often called "shooting stars"—are tiny remnants of comets and asteroids: bits of dust and chunks of ice and rock that have drifted among the planets for billions of years. They orbit around the Sun, just as Earth does, and occasionally Earth plows into them. The doomed particles heat up quickly as they zip into the atmosphere at speeds of at least forty thousand miles (64,000 km) per hour. The friction incinerates them about fifty miles (80 km) above Earth's surface. Faint meteors are as small as a pebble, while bright ones might be the size of a grape or a walnut. The rare bigger ones, perhaps baseball-sized, often explode in spectacular balls of fire called *bolides*.

Earth's blanket of air doesn't protect against even larger chunks of cosmic debris. Some of these survive the flames and strike the ground, where they usually land harmlessly as meteorites. No one has died during such an impact in recorded history, but astronomers think it's just a matter of time. An event similar to the 1908 Siberian explosion could kill many thousands of people if it happened over a populated area.

Several research teams have dedicated their telescopes to searching for any such objects that might be headed our way. Even so, it would be hard to prevent a comet or an asteroid from hitting Earth. Nor are the searches likely to provide enough warning of incoming objects the size of a house or a sports stadium. Near misses are common. In January 2002, an asteroid named 2001YB5 zipped past Earth just 375,000 miles (600,000 km) away, about twice the distance between Earth and the Moon. Astronomers saw this thousand-foot-wide (300-m-wide) rock only a few weeks earlier and would have been powerless to steer it away or destroy it if it had headed directly at us. Such intruders might hit Earth as frequently as once every one thousand to ten thousand years. If one landed in the ocean, the resulting giant waves could destroy low-lying coastal areas.

Gigantic asteroid impacts are far more rare, but geologists believe they have extinguished more than half of Earth's species several times. The asteroid that wiped out the dinosaurs probably was about six miles (10 km) wide—a rather small object by solar-system standards. The impact unleashed ten thousand times more energy than Earth's entire arsenal of nuclear weapons. It gouged a 120-mile-wide (200-km-wide) crater near Mexico's Yucatan Peninsula, although the crater was not the culprit behind the global death. Instead, the explosion kicked up vast amounts of dust, soot, and water vapor into



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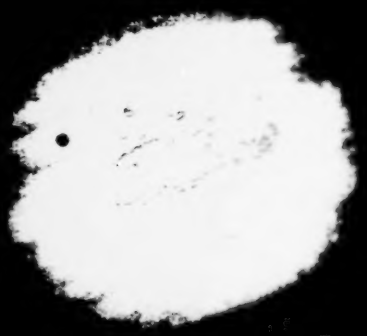

the planet's atmosphere, blocking sunlight for years. When most plant life died out, the dinosaurs soon followed. Such random catastrophes, repeated a few times over spans of hundreds of millions of years, paved the way for certain species to evolve and dominate while others perished.

While most crashes within the solar system cause devastation, some have actually created new worlds. The ultimate such collision in Earth's history happened a mere fifty million years or so after the planet formed 4.5 billion years ago. In the infant solar system, small "protoplanets" collided and coalesced in a violent process called *accretion*, gradually building up the rocky planets we see today. One of the last such protoplanets, astronomers believe, was a Mars-sized object that smashed into the young Earth. The shattering collision melted both bodies and cast much of the rock back into space. That material quickly clumped together to form our companion, the Moon. "Without impact, Mercury, Venus, Earth, Mars, and the Moon would not exist," Carolyn and Eugene Shoemaker wrote. "In a sense, the last stage of planetary accretion is still going on—albeit at a very slow rate."

Today, as planets orbit the Sun and moons orbit their planets, the solar system is quieter than it was in its youth. Still, gravitational interactions can play tricks. For instance, most comets drift inward toward the Sun from great distances, far beyond the orbit of Pluto. If a comet passes too close to a large planet, especially giant Jupiter, gravity bends the comet's path into a brand-new orbit. A close brush with Jupiter is much more likely to slingshot a comet out of the solar system entirely than to aim it toward Earth. In this way, Jupiter protects Earth and the rest of the inner solar system from a greater bombardment of comets, making it possible for life to arise during periods of relative calm.

On occasion, Jupiter captures a comet rather than expels it. This happened with Comet Shoemaker-Levy 9, discovered by the Shoemakers and amateur astronomer David Levy. When they found the comet, the astronomers realized that Jupiter's gravity had rent the weak, icy comet into bits. It had broken into more than twenty pieces, a "string of pearls" (shown above) each perhaps a quarter of a mile wide. The fragments looped around Jupiter and struck the planet for six days in July 1994—the first cosmic collisions witnessed by modern astronomers. The impacts occurred on the planet's far side, just barely out of direct view, but the crash sites soon rotated into view as enormous brown scars in Jupiter's atmosphere. Each blast produced about as much energy as 25,000 megatons of TNT.

People alive today may never again witness such dramatic motions in our solar system. However, astronomers need only look deeper into space to see motion on ever-grander scales that sculpts our Milky Way galaxy, our galactic neighbors, and the universe itself.

The majestic crashes of galaxies

Just as the Sun has its retinue of planets, asteroids, and comets, the Milky Way is surrounded by clumps of gas and tiny groups of stars called dwarf galaxies. The Milky Way also sits within a vast cocoon of *dark matter*, massive material that astronomers have neither observed nor identified. This matter exerts a drag on the gas and the galaxies that travel through it, just as a runner moves more slowly in water than in air. The drag forces the gas and the dwarf galaxies to spiral into the Milky Way, a slow process that takes hundreds of millions of years. Over its lifetime of at least ten billion years, the Milky Way has acquired countless such fragments, building up its mass to the mature galaxy we see today.

Most of these mergers are benign. Stars in galaxies are so widely separated that even when the Milky Way consumes a dwarf galaxy, stars rarely collide. Rather, the newly acquired stars simply spread out and blend with those in the Milky Way until most traces of the smaller galaxy vanish. Gas clouds within the merging galaxies are much bigger than the stars, so they do collide. Those clouds are chock full of the raw materials needed to make new stars. When they hit each other, the shock waves can trigger pockets of gas and dust to collapse and then contract into newborn stars. The death of a small galaxy, then, can lead to a blaze of glory of new life within the Milky Way as fresh generations of stars arise.

When two fully mature galaxies collide, the results are far more spectacular. Telescope studies of many pairs of crashing galaxies reveal giant arcs of stars—many millions of suns, all flung into space by the intense gravitational tides raised by the collision. The galaxies may pass completely through each other, but the powerful gravity of their dark-matter cocoons draws them back together into a featureless blob of stars.

Such a fate awaits the Milky Way in a few billion years. Our galaxy is locked in a waltz with its nearest large neighbor, the Andromeda galaxy. Andromeda is twice the size of the Milky Way, so its gravitational forces will distort our galaxy beyond recognition as the two spirals approach each other. "It will be a major car wreck, and we're the

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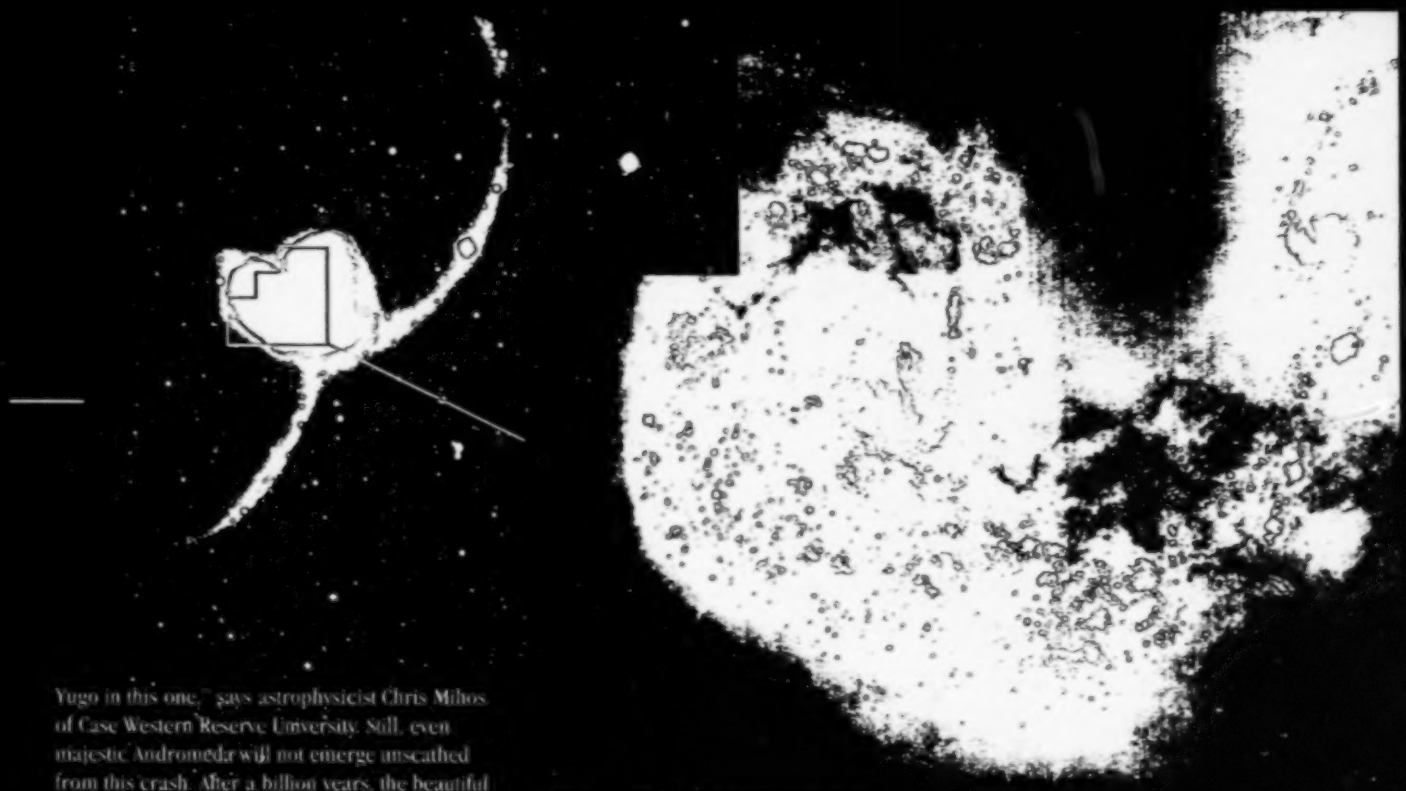


Known informally as the "Antennae galaxies," the ground-based telescopic image *(left)*, shows the result of the collision of two galaxies in the constellation Corvus. The Hubble close-up image *(right)* shows that this cosmic crash site is a nursery for new stars.

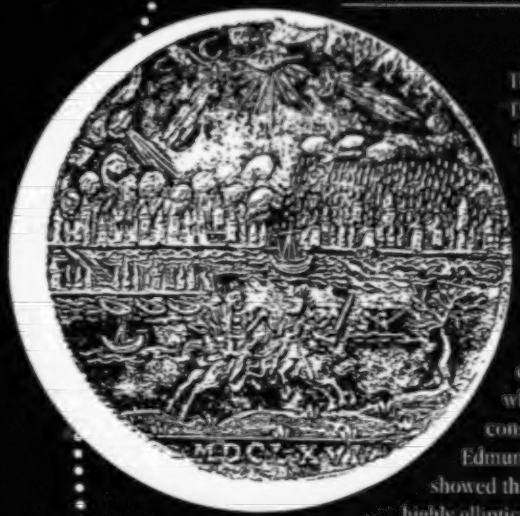
Yugo in this one," says astrophysicist Chris Mihos of Case Western Reserve University. Still, even majestic Andromeda will not emerge unscathed from this crash. After a billion years, the beautiful spiral patterns in both galaxies will disappear as the Milky Way and Andromeda merge completely.

This galactic pileup may not matter to future inhabitants of our solar system. By the time Andromeda looms nearby, our own Sun will have run out of its nuclear fuel, incinerating Earth as it expands into a vast red giant. The aesthetic appearance of our galaxy is likely to be far less important to our descendants than finding another suitable place to live.

Our ever-growing cosmos Individual motions of galaxies pale when compared to the granddaddy of them all, the expansion of the universe. Driven outward by the force of the primordial big bang about fourteen billion years ago, space itself expands at a fantastic rate and carries galaxies along for the ride. For years, astrophysicists debated whether this growth would continue forever or whether gravity would draw all galaxies back together into a "big crunch," the ultimate collision indeed.

Recent studies in astrophysics point to an unsettling answer: The universe not only will continue to grow, but it will expand faster and faster as time goes on. Scientists do not yet understand the bizarre property of space that would lead to this apparent acceleration. But if it proves true, then collisions in our universe will grow rarer as galaxies drift farther apart. In time, the violent crashes that make life in our universe so interesting—and so treacherous—will no longer occur. ➤

COSMIC DESTINY?



This medallion, with the inscription "Thus God Punishes," depicts a comet that was visible over London in 1666. It links the comet's appearance to a series of devastating events suffered by London in the mid 1600s, including the Bubonic plague and a fire that almost destroyed the city.

Most people of the time believed in astrology, which maintains that celestial bodies influence or foretell what happens on Earth; a comet was considered a dire omen. Astronomer Edmund Halley (1656–1742), however, showed that comets have predictable, although highly elliptical, orbits around the sun—rather than appearing randomly as signs of approaching disaster. Of course, if our planet should collide with the head of a comet, it would be dire indeed.

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Have you ever felt your skin "crawl," or remarked that your life is caught on a treadmill? Many of us use these common metaphors. At the cellular level, though, *crawling* and *treadmilling* are words to be taken literally. They describe motions that occur constantly, helping to keep us alive. But what enables our cells—and, in fact, most living cells—to lead such bustling lives?

If you could peek inside one of your cells, you'd find that long protein fibers form a matrix called the *cytoskeleton*, which is curiously similar to scaffolding found at construction sites. Just as sections of scaffolding can be reconfigured, the fibers of the cytoskeleton, which consist of many subunits, can be expanded or downsized, or taken apart and reassembled into a different shape or at a different location within the cell.

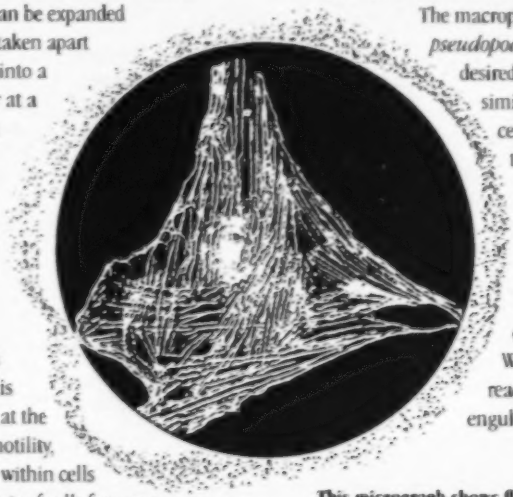
The cytoskeleton helps maintain a cell's shape, but its structural flexibility allows the cell to *change* its shape as well. This shape-shifting is at the root of cellular motility, both movements within cells and the movements of cells from one location to another. Without this capacity for motion, immune cells couldn't penetrate infected tissue, muscle cells couldn't contract, and cells couldn't divide. Each of these processes—and many more—begin with a change in a cell's internal scaffolding.

Several different types of fibers make up the cytoskeleton. Molecules of the protein actin link together to form the smallest fibers in the scaffold, threadlike chains known as *microfilaments*. As actin molecules are added or removed, the microfilaments grow longer or shorter. The fibers can combine to form three-dimensional networks, or bundles that are similar to threads twisted into a rope, depending on the needs of the cell.

Let's take a look at a particular type of cell called a *macrophage* ("big eater"), and the role microfilaments play in this cell's ability to move. The job of a macrophage is to search for and destroy bacteria and other invaders that don't belong in the body, as well as to recycle the molecular components of dead and damaged body cells. (Macrophages in the human spleen and liver dispose of more than a hundred billion aged blood cells a day!)

When bacteria invade the body, a macrophage precursor (a white blood cell called a *monocyte*) receives a signal from other immune cells that are first on the scene. The monocyte responds to the signal by traveling through the bloodstream to the infection site. It squeezes through the tiniest blood vessels, the capillaries, and enters the tissue where it quickly transforms into a large, voracious macrophage. Now, however, the macrophage must traverse solid flesh to reach the bacteria. To achieve its goal, it crawls.

The macrophage extends a *pseudopod* ("false foot") in the desired direction, which is similar to the way a one-celled *Amoeba* moves through its environment. The surface of the pseudopod attaches to the underlying tissue, the trailing edge of the cell retracts, and the crawling cycle repeats. When the macrophage reaches the bacteria, it engulfs and digests them.



This micrograph shows fluorescently stained microfilaments of the cytoskeleton, which extend throughout the cytoplasm of a cell. Different fluorescent stains make different cytoskeletal components observable.

Movement of actin microfilaments inside the macrophage creates a pseudopod, with the cell contents simultaneously flowing into this false foot. A microfilament can move in a particular direction by adding new molecules at one end more quickly than at the opposite end. This process, known as *treadmilling*, is thought to be the key to pseudopod formation and many other types of cell movements.

Cell motion is abundant far and beyond the movement of cells in their environment. Movement within cells is fundamental to activities that include reproduction and resource distribution.

Most cells reproduce by dividing in two on a regular basis, primarily to allow an organism to grow or to replace damaged or aging cells. Before it divides, however, the cell has to partition its contents so that each new cell receives everything it needs to function properly. The correct distribution of chromosomes is critical, because each newly formed cell needs a complete set. A key "mover" of the chromosomes during division are structures called *microtubules*, the largest of the cytoskeletal fibers. Microtubules are long, hollow, flexible rods that, like microfilaments, extend and retract by adding or removing their subunits, in this case molecules of a protein called *tubulin*.

To distribute chromosomes, microtubules first extend from two organizing areas at opposite sides of the cell, and then they attach to the center of each duplicated chromosome. Next, the microtubules shorten, pulling the chromosomes to opposite sides of the cell. When all of the cellular components are partitioned appropriately, actin microfilaments, and another cytoskeletal protein, myosin, form a ring around the center of the cell. The ring contracts, pinching the cell in two. Thanks to the dynamic cytoskeleton, each new cell has the proper number of chromosomes and the materials it requires.

Many cellular components are produced in one part of a cell but are used in other parts. The "highways" within a cell that distribute these components are frequently built of microtubules.

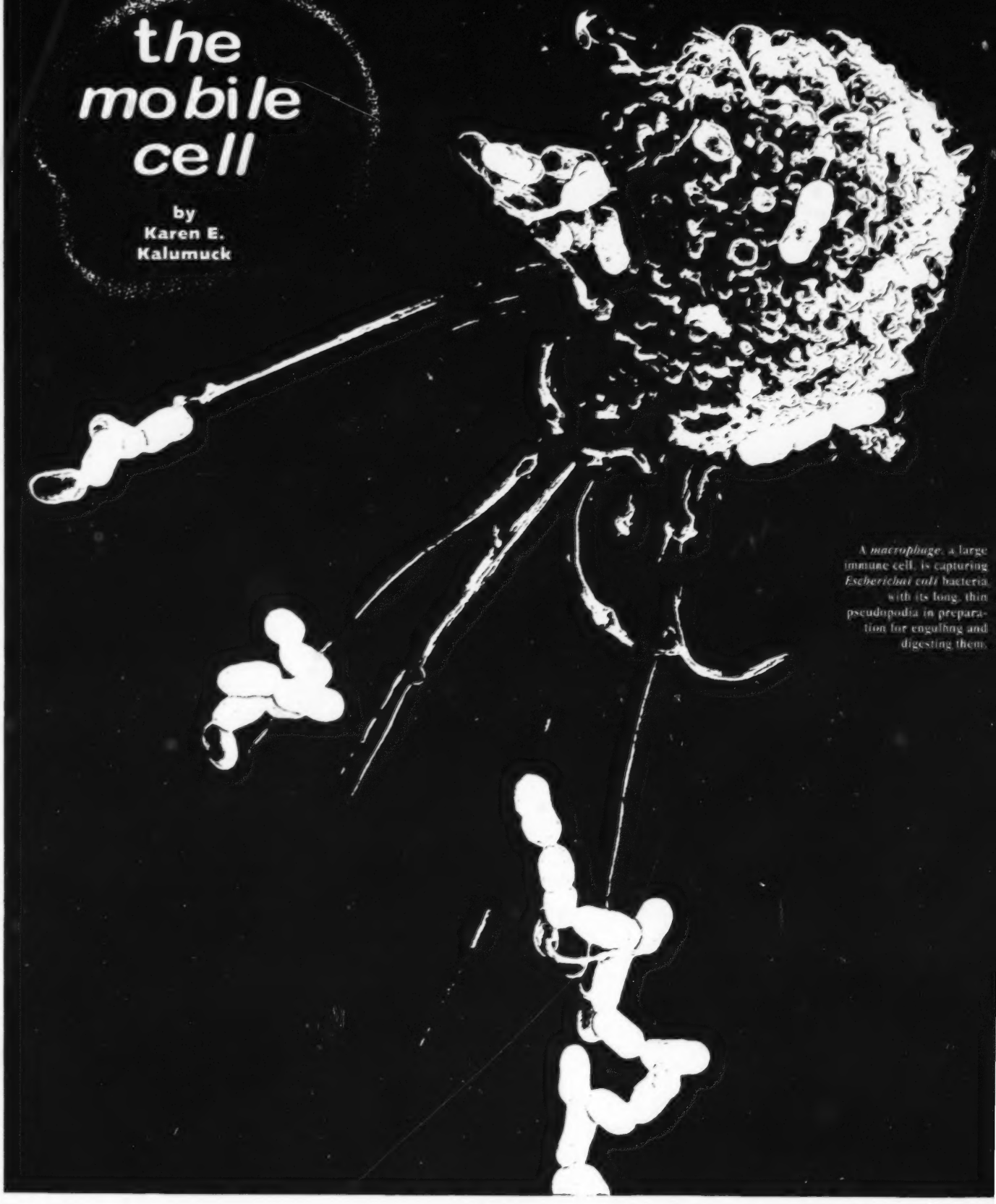
Consider, for example, a *neuron*, or nerve cell. It has a roundish cell body with two major projections extending from it in opposite directions. One projection, called a *dendrite*, accepts signals from other neurons. It's typically a short, branching structure. The other is a long, thin projection called an *axon*, which conducts signals away from the cell body. The axon can be extremely long—around three feet (1 m) in some cases.

Many of the cellular components that the axon needs to function properly—for example, structures called *mitochondria* that are essential for the production of energy—originate in the cell body. How does the tip of the axon, an astronomical distance away (from the cell's perspective) obtain the materials it needs? The answer is that microtubules are present along the entire length of the axon, and the needed components, including mitochondria, travel from the cell body along these cellular "highways" to their destination.

These are but a few examples of the whirlwind of motion that's constantly occurring within our bodies. The next time you feel like you're on a treadmill, stop a second to appreciate that, at the cellular level, that's a very good thing. ➤

the mobile cell

by
Karen E.
Kalumuck



A *macrophage*, a large immune cell, is capturing *Escherichai coli* bacteria with its long, thin pseudopodia in preparation for engulfing and digesting them.

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The paths of paths

by Steven Vogel

The larger photo shows deer trails meandering across a California hillside. Large animals, including people, often prefer longer distances to short, steep ascents. On level ground, though, we usually opt for the most direct route. The many paths that crisscross Harvard Yard in Massachusetts *(inset)* acknowledge our penchant for a straightforward approach.

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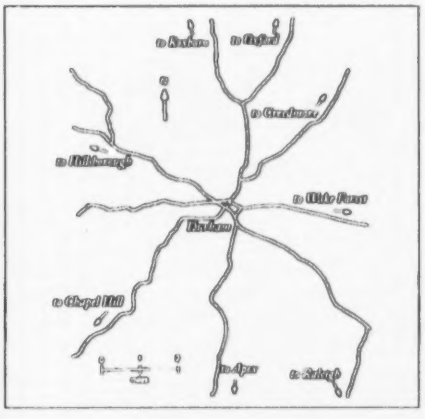
Like lots of other creatures, we humans follow paths. Like just a few, such as some ants, we're road builders as well. What sets the specific courses of our paths and roads?

I live in the city of Durham, which is nestled in the gentle hills of the Carolina Piedmont. Originally just a place where two railroads crossed, Durham lacks any mountain, river, or harbor. From it, one can head in any direction on radial arteries that, before recent reroutings, meandered as if intent on disorienting the stranger. Ground-level experience—especially walking or bicycling—reveals that our radial roads don't go up and down the way the secondary streets do. Their routing attempted to avoid the ubiquitous slopes of the Piedmont without, as is now the custom, digging and filling. Why such antipathy toward slopes? Dismissing it as pure cultural artifact would be a mistake: Muscle mechanics made the mess.

In places like Durham, where roads twist and turn, frustrated drivers imagine that they track the wanderings of long-dead grazing animals. More likely, our forebears wanted quick and easy passage



from one place to another. A straight line may be the shortest path, but shortest needn't be quickest or easiest. Only recently—within two hundred or so years—has land transport meant anything but walkers, pack animals, and animal-drawn vehicles. Since muscle moved them all, a look at some simple muscle physiology and biomechanics might put us on the right track.

Consider what happens when an animal goes uphill. To the ordinary work of personal maintenance and locomotion, the animal adds gravitational work as it lifts the mass of its body. Such work incurs a metabolic cost that's directly proportional to body mass. So going uphill costs a larger animal relatively more than it costs a smaller one. A chimpanzee running up a fifteen-degree slope uses about 50 percent more energy (and consumes 50 percent more oxygen) than when it runs on level ground. The considerably smaller squirrel cares less about the grade of its path. For the squirrel, simply being and moving cost relatively more, ascending relatively less, and it climbs a tree almost as fast as it runs on the ground.

A given slope slows a horse and wagon more than it slows a horse alone; it slows a horse more than it slows a person, and it slows a person more than it slows a dog, relative to the speed at which each travels on level ground. Even slight slopes tax a horse pulling a loaded wagon. Durham was a market town, and farmers could haul their produce into town more easily if their horses, mules, or oxen didn't have to pull uphill. Expeditious transport meant level, not direct.

Tropical leaf-cutting ants build roads, along which each ant carries a piece of leaf homeward. Unlike what we do, the ants route their roads to minimize distance, often going straight up steep obstacles rather than taking a longer route around.

Still, even small creatures—if not as small as ants—do expend extra energy when slopes get extreme. Cockroaches persuaded to run on treadmills consume twice (but only twice) as much energy climbing a forty-five-degree slope as when walking

Sometimes it's an uphill battle.

on the level. They burn three times (but only three times) the energy on a fully vertical treadmill.

Until recently, humans walked long distances. In mass, we lie between squirrels and horses, so slope matters more to us than it does to squirrels, if not as much as to horses. A five-degree upward slope doubles one's energy cost at a constant speed, so it's equivalent to carrying a load equal to one's body weight. Ten degrees triples the cost, equivalent to carrying twice one's weight. When a person slows down while climbing, that just stretches the cost of gaining altitude over a longer time.

So say you want to lay a trail up a steep mountain. How should you route it? Data from inclined treadmills tell us that steeper is better when gaining altitude is the goal, but only up to a point. Each increment of altitude increases the slope but decreases the distance you have to cover. Up to twenty-five degrees, the two balance reasonably well. Above a slope of twenty-five degrees, we do better if we take a longer, gentler route.

Reality matches the treadmill's predictions remarkably well. According to one study (which limited itself to footpaths used by unencumbered humans) mountain paths go directly uphill only at slopes of less than 25 degrees. At least they do so at altitudes below ten thousand feet (3,000 m) or so. Higher paths are less steep, which seems sensible if you consider that, with decreasing atmospheric pressure, the oxygen available at ten thousand feet is 30 percent less than the oxygen available at sea level.

In short, while the big animal may enjoy a significant advantage in overall cost of transport and a slight advantage in speed, it suffers a disadvantage on slopes. We should be quite impressed that Hannibal brought the Carthaginian elephants over the Alps. No preexisting path could have anticipated elephant traffic, and picking elephant-tolerant paths must have cost both time and distance.

Muscle power affects more than the slopes of paths and roads. Padded collars, a medieval development, allowed people to harness one horse behind another. Using collars, long teams of paired horses (more than two would exceed road width) could pull a wagon. Such serial hitching helped in rough country, and the street designs of some cities still reflect its use. The broad avenues of Salt Lake City, in the American West, and Ballarat and Bendigo, in inland Australia, allowed long teams to make U-turns. Lengthwise straps and ropes do fine for pulling, but wagon trains can't easily back up—one can't push on a rope! On the other hand, few wheeled vehicles of any kind entered the typical North African town, since pack animals provided better transport across sandy desert. And with urban land none too plentiful (especially in walled cities), they developed their characteristic narrow, twisty streets—useful also in defending against invaders.

Muscle power affected even the locations of medieval settlements. An ox may pull harder, but it goes slower than a horse, so the farmer who uses oxen must live in a hamlet close to his field. Where farmers used horses, villages were more widely spaced and larger. And since horse-drawn wagons can go about twice as far in a day as those drawn by oxen, where horses provided transport, market towns were fewer, larger, and farther apart.

In such matters, as in so many others, there's biology behind history. ➤

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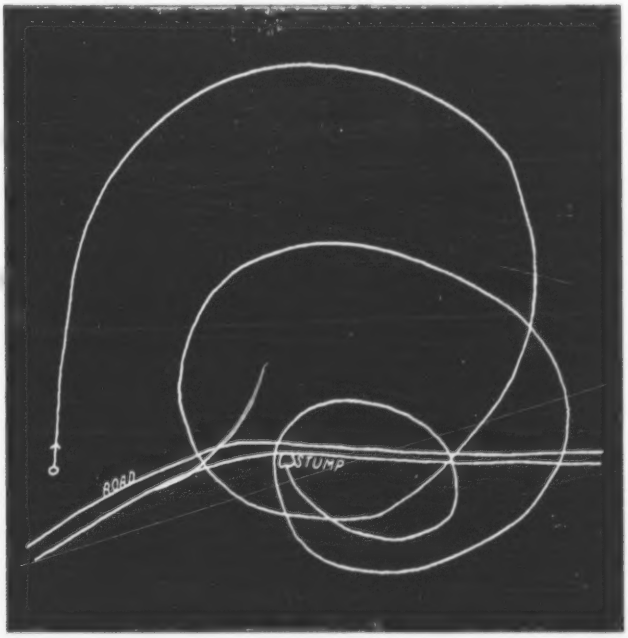
Fragments

by Pearl Tesler

Early in the twentieth century, American zoologist Asa Schaeffer noticed that an amoeba placed on a cylindrical surface always moves in a spiral path around the cylinder. Intrigued, Schaeffer blindfolded a right-handed friend in a country field and instructed him to walk a straight line. Shown at right is Schaeffer's plot of his friend's progress—a clockwise spiral that culminates, alas, in the friend tripping over a tree stump.



Try this: Jab the tip of a ballpoint pen into a Superball, then drop them together onto a hard floor, ball end down. Watch out: One of these items will fly sky high—and it's not the ball. At work here is a transfer of "kinetic energy," the energy of motion. As it recoils from the floor, the bouncy Superball gives almost all of its kinetic energy to the pen.

Yo-yo dieting isn't just a figure of speech. In the sixteenth century, the seemingly innocuous yo-yo was used by hunters in the Philippines to capture their dinner. Made from heavy wooden disks and twine, the yo-yo was flung in hopes of ensnaring a fleeing animals legs.

Acrobatic break dancing seems to defy the laws of physics.

Has anyone ever tried to tell you that the *Coriolis effect*—the apparent deflection of moving objects due to the rotation of the

earth—makes toilet bowls flush counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere? Don't buy it. Toilet water doesn't move fast enough or far enough to experience an appreciable *Coriolis force*. The design of the bowl is far more likely to determine the direction of flow.

When nineteenth-century botanist Robert Brown looked through his microscope and saw pollen grains jittering in water, he thought the motion was a sign of life—until he saw the same dancing motion in dust, soot, and even a powdered fragment of stone taken from the Sphinx. As it turns out, all tiny particles are smacked this way and that by molecules in the surrounding air or water. Brown's discovery provided the first real evidence for the existence of molecules.

Here's a party trick that's also a safe bet: Hold the end of a dollar bill between your fingertips so that it hangs down lengthwise. Have a friend hold his or her thumb and forefinger about an inch apart on either side of the bill with the picture of George Washington level with the fingers. This person's goal will be to catch the falling dollar bill when you drop it without warning.

Odds are that the buck will slip through just about anyone's fingers. The time it takes for most people to see the bill falling and react by closing their fingers is about 0.18 seconds. In this amount of time, the dollar has fallen over six inches—in other words, it's long gone.

The soul has many motions, body one. —Theodore Roethke

Until the 1890s, the U.S. Patent Office refused to accept patents for "heavier than air" flying machines, claiming that these were physically impossible.

"When a cat is dropped, it always lands on its feet, and when toast is dropped, it always lands buttered-side down. Therefore, if a slice of toast is strapped to a cat's back, buttered side up, and the animal is then dropped, the two opposing forces will cause it to hover, spinning inches above the ground. If enough toast-laden felines were used, they could form the basis of a high-speed monorail system or a generator."

—Department of Perpetual Motion,
University of Slough
www.university-of-slough.org.uk

In fleeting wisps, smoke reveals invisible movements of the air.

a

"The aim of every artist," William Faulkner once said, "is to arrest motion, which is life, by artificial means."

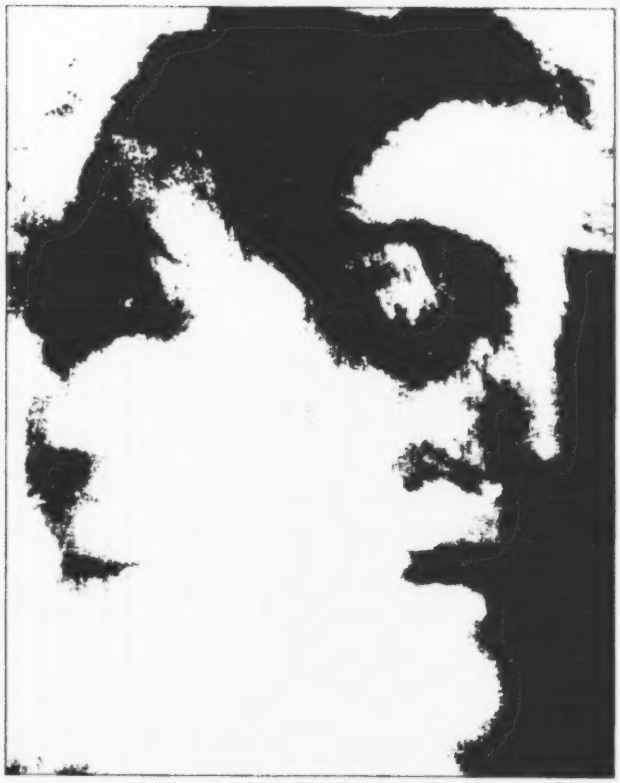
This is especially true of photographers, who can freeze even the fastest movements with the click of a button. In doing so, they let us see beyond the limits of our eyes.

A photo-essay

by Amy Snyder

b

moving pictures . . .

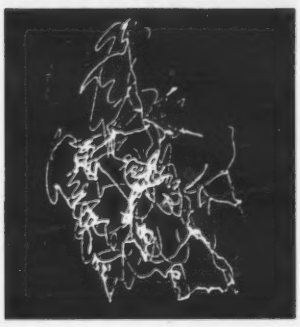


c

Photography is full of paradoxes: To show motion, it must stop motion. And while it reveals truths, it also creates them.

"The convention of the blur comes from photography," artist David Hockney pointed out. "It's what happens when motion is compressed onto a chemical plate. We've seen so many photos of blurs that we now think we actually see them in the world. But look sometime: you don't."

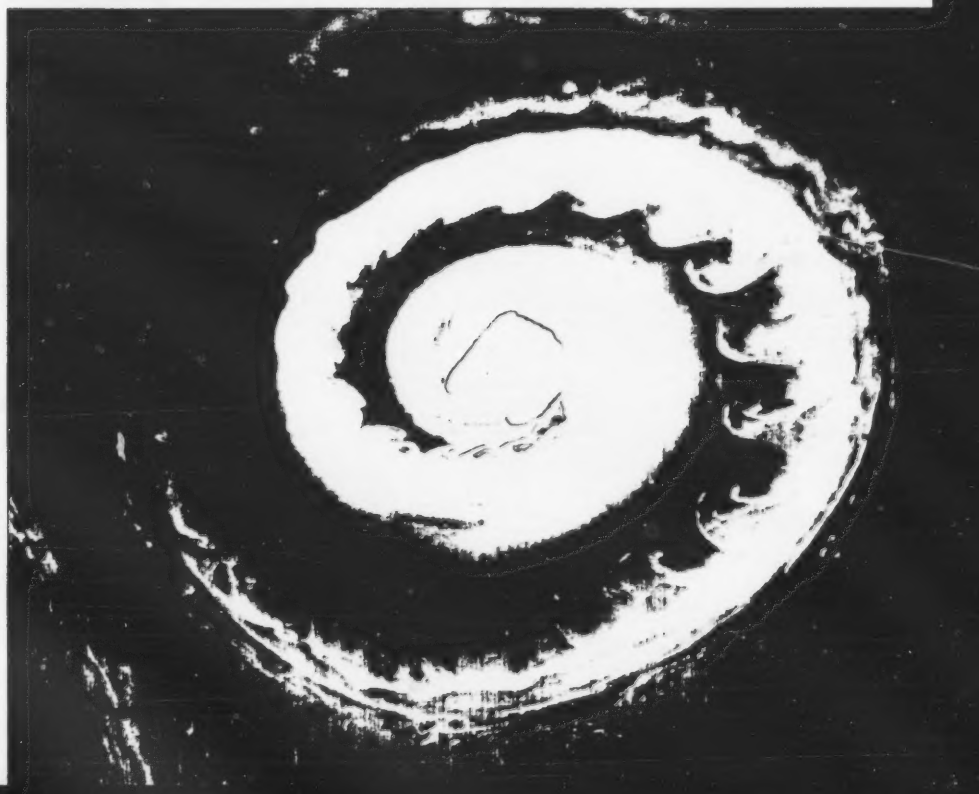
d



e

"Of all the means of expression," Henri Cartier-Bresson wrote in 1952, "photography is the only one that fixes forever the precise and transitory instant. We photographers deal in things which are continually vanishing, and when they have vanished, there is no contrivance which can make them come back again."

f



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For technical information on how these images were photographed, see page 28. ▷

Plants stay attached to the earth, so we often think of them as immobile. But in fact, plants move constantly. You can see plants dancing in time-lapse photos, waving their shoots, leaves, and tendrils in the air. They fight against the forces of gravity to grow toward the sky. They forage for the light, water, and minerals that sustain them. Some even have the capacity for speedy action, snapping and leaping on prey or on insects that will carry their pollen. And plants grow upward from the earth's surface—some to several hundred feet in the sky—inhabiting new territory with each leaf and twig.

Dancing with grace Naturalist Charles Darwin was among the first to challenge the undeserved reputation of plants as sticks-in-the-mud. More than a century ago, he observed plants and exhaustively recorded their movements in two books, *On the Movements and Habits of Climbing Plants* and *The Power of Movement in Plants*. Darwin reported on his classic experiment: He attached a thin glass filament tipped with black wax to the tendril of a growing vine under continuous white light. The filament, acting as a pen, drew the path of the tendril's elliptical and spiraling ballet on a sheet of glass. Repeating the test on the shoots of beans, squash, and other plants, Darwin observed similar ellipses. His published diagrams, which he called "circumnutations," look like dance patterns.

The reason for these plant pirouettes remains mysterious. Some have suggested that when shoots inadvertently lean in one direction, they may "feel" which way is up and overcorrect, swinging back past vertical and setting off a cycle that leads to elliptical movements. But experiments on two SpaceLab missions and two NASA space shuttle flights undermine this model: Plants dance even in the absence of gravity. So some researchers have proposed that circumnutations result from internal oscillations in growth. At the tip of a shoot, cells multiply and elongate in a spiral pattern. Hormones and their associated reactions can move around the tip in waves, passing through pores that connect all of a plant's cells together. These waves might generate differences in growth along their path, establishing a rhythm that we witness as an elliptical dance.

Reacting to gravity Even if gravity doesn't cause Darwin's tiny circumnutations, it does make roots bend toward the earth and shoots head toward the sky. These *gravitropic* movements (movements toward or away from the earth's gravitational pull) are most often triggered by starch-laden particles called *statoliths* that settle to the bottom of plant cells. When statoliths exert a force on the cell floor, certain hormone "gateways," molecules that control the entry and exit of the growth hormone called *auxin,* recognize that they belong down there as well.

Turn a plant stem on its side and after the starch particles shift from the old floor—now a side wall—to the new one, the hormone gates move, too. Auxin then travels downward through the floor to the underside of the horizontal stem. There, it loosens fibers in the cell wall, allowing faster growth that causes the stem to bend upward.

In roots, auxin travels in a different pattern, circulating down the center of the root and back up the sides. It also produces a different result—downward motion.

Searching for sustenance Although vegetation can't smell or chase food, plants appear to sense and pursue the light, water, and nutrients they need. And, as with gravitropism, responses differ for roots and shoots. In a process called *phototropism,* shoots bend toward the sun, while any roots exposed to light tend to grow away from it. Roots also pursue underground water sources by *hydrotropism*.

Vines seek support to climb into the light. They explore and sense their environments like hunting dogs swinging their noses around to get a whiff of the fox. Small-leaved shoots of liana, a tropical rainforest vine, skitter across the ground hunting down light. When they reach an open spot, they climb up any tree that's handy, hungrily devouring the sun's energy as they move—growing larger leaves, and eventually forming their own tree crown in the forest canopy.

In many plants, including corn and oats, hormone movements facilitate phototropism. The hormone auxin travels across the stem to the shady side where it hastens growth. The longer cells on that side force the stem to bend away from the dark and toward the sun's energy. In some other plants, it appears that molecules inhibit growth on the sunny side to produce the same effect: elongated cells on the shady side that cause a bend in the stem. It's also possible that both mechanisms may be involved in the same plant, as organisms often have redundant ways to produce the same effect.

Acting swiftly Most plants dance and hunt at a slow clip, but a few speedsters surprise us with movements so rapid they seem truly animal-like. The pollen-laden stamens of the trigger plant lie in a cocked position, like mousetraps ready to spring. At the touch of an insect, the stamens pounce, throwing their loads of pollen onto the bug for transport to another flower. Similarly, if a fly brushes the trigger hairs on the leaf of a Venus's flytrap, it snaps shut in about a second, confining the bug in a vegetative coffin. Changes in cellular water pressure factor into these quick responses to touch, but even though scientists have studied the Venus's flytrap since before Darwin's time, they still don't fully understand the mechanisms by which the traps work.

The mimosa, or sensitive plant, also moves rapidly in response to touch. A sudden swat and its leaves flop down from their perky postures to dangle vertically like snoozing bats. But if one leaf of the plant is gently stroked, the leaves on that branch will droop in sequence. When the signal reaches the stem, that whole branch will fall and the signal moves to the other branches, whose leaves all fold down like dominoes in semi-slow motion. A short time later, the leaves and branches rise back up.

This up-and-down action of the mimosa originates in the movement of water from the lower to the upper side of a caterpillar-shaped organ, the *pulvinus,* located at the base of the leaf. These movements are provoked by ions (charged molecules) traversing cell membranes. At rest, a living cell steadily pumps ions from one side of its outer membrane to the other to maintain a difference in charge. For some reason, touch causes the Mimosa to release ions back across the membrane, reducing the discrepancy between the amount of charge on the two sides. This shift moves rapidly through the cells in the leaves and stems to the pulvinus. In response, the cells on the underside of the pulvinus jettison their water so that they collapse, accordion style. The ejected water swells

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plants on the go

by Katharine Miller

Open *(below)*, the Venus's flytrap *(Dionaea muscipula)* entices insects by secreting nectar along the rim of the trap. Once it captures an insect *(right)*, the trap stays closed for about a week while the prey is digested. This plant adapted to a partially carnivorous life because the sandy soil of its native habitat in the southeastern United States can't supply all the nutrients it needs.

The sensitive plant, *Mimosa pudica*, in its normal posture *(above)* and just after it's been touched *(left)*. Mimosa comes from the Latin *mimus*, meaning "mime," because the plant appears to mimic an animal's response to touch.

The drawings *(right)* show the results of experiments with plant movement conducted by Charles Darwin in the late 1800s. Darwin attached a marking device to plant shoots that plotted their movement on a vertical sheet of glass for about half a day. Darwin explained the far-left drawing as follows: It "moved seven times from side to side, and thus described three-and-a-half ellipses in ten and three-quarter hours; each being completed on an average in three hours and four minutes."

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the upper side of the pulvinus, which takes on an inverted-U shape and rapidly pushes the leaf or branch into the down position. The return to vertical occurs as the ions gradually go back to their original positions, drawing water with them.

Invading new territory

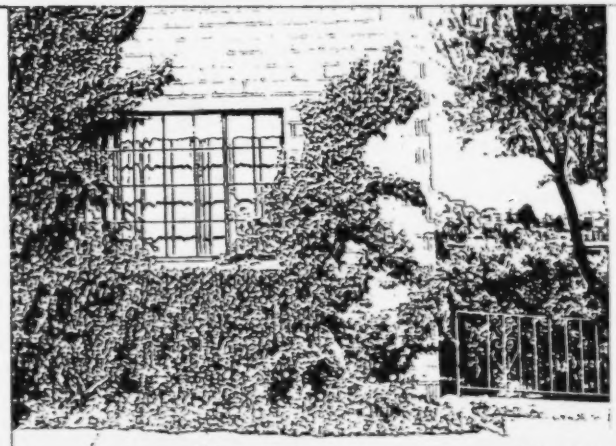
Invaders move from one place to another—in many ways a more dramatic shift than changes in the posture of an otherwise stationary plant. But these plants relocate slowly, and the process is less likely to be called "movement" by the casual observer.

Invaders move by growing, and in this sense all plants are invaders, reaching toward the sky. But to satisfy skeptics that a plant can actually change its address, we need look no farther than common ivy. As it extends along the ground, this vine sends down new roots and stretches through a fence into the neighbor's garden. Digging up the roots where the ivy was first planted will not eradicate the vine, because it doesn't live there anymore. It moved next door.

In a tree version of the same story, the banyan, native to India and Bangladesh, starts as a seed dropped on another tree during a bird's fly-by. From there, the seed sends a cluster of aerial roots down to the ground. The cluster develops into a trunk capable of supporting heavy horizontal branches that send down still more roots. Eventually, the one tree becomes a forest of trunks and branches covering as much as an acre (4,000 m^2) of land. As the older roots and limbs die off, the monstrous tree moves to new turf, "walking" across the forest.

Moving at a plant's pace

In comparison to animals, plants seem quite slow. To observe most types of plant movements, we must be very patient: New plant shoots make one circumnutational rotation in about an hour; phototropic and gravitropic bending are apparent within a day; and the expansive growth of a banyan takes perhaps a century. But even if we can beat plants at the hundred-yard dash, consider this: No animal can grow as tall or live as long as an ancient redwood tree. ➤



The "basket tree" *(right)*, actually six sycamores grafted together, is one of many fanciful designs that Axel Evlandson *(below)* coaxed from living trees beginning in the 1920s. More easily manipulated than trees, ivy *(above)* can be persuaded to crawl up houses and along fences. Left to its own devices, however, the ivy may decide to adorn the neighbor's house as well.

Try This!

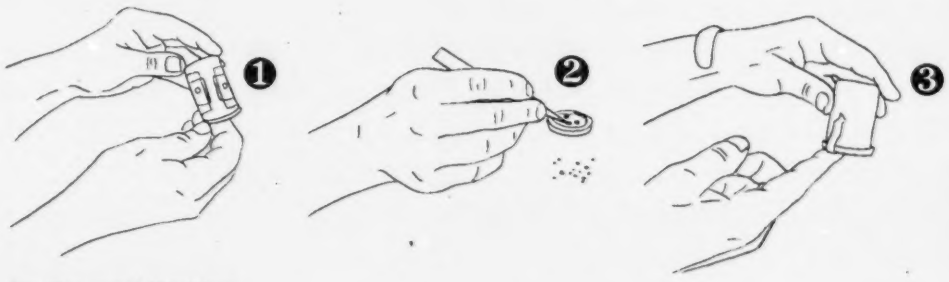
by Karen E. Kalumuck

Plant Tropisms

Find out what happens when you turn seedlings on their sides, and explore whether or not plants "like" one color of light more than others.

Materials
(for both experiments)

- 2 black 35-mm film canisters with lids
- 1 one-hole paper punch, or electric drill with 13/64" drill bit
- scissors
- colored plastic film sheets (red, blue, green)
- clear tape
- paper towel
- radish seeds
- masking tape
- fluorescent light source (40-watt bulb)
- permanent marker or white correction fluid

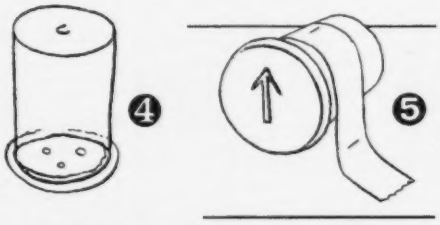


To Do and Notice

Experiment 1: Phototropism—Responding to Light

1. Use the hole punch or drill to make three holes in a film canister, each about halfway between the top and bottom of the can and equally spaced around the circumference of the can. Cut one square each of red, blue, and green film, large enough to cover the holes. Use clear tape to secure one square over each hole. Be sure that the holes are covered completely with the colored film. You've just made an incubation chamber with one red, one blue, and one green "window."
2. Cut four layers of paper towel to fit snugly inside the film can lid. Moisten these so that they are very damp, but not dripping wet, and the layers are in continuous contact with each other. Place three radish seeds on the paper towel so that they form a triangle with each seed about a third of an inch (7.5 mm) from the others. Invert the canister over the lid and seeds, and snap it into place. Use a narrow strip of masking tape to connect the lid and body; this will allow you to make sure that the orientation of the windows to the seeds remains the same throughout the experiment.
3. Place the incubation chamber under the fluorescent bulb so that each window receives an equal amount of light. Leave it undisturbed for four to five days, then check the progress. Are the seedlings growing straight up? Are they bending toward a particular window?

   If the seedlings are still very short, remoisten the paper towels, replace the canister, and check again in a few days. Be sure to replace the canister so that the colored windows are in the original orientation.



Experiment 2: Gravitropism—Responding to Gravity

4. Make a second—but windowless—incubation chamber. Place four layers of moistened paper towels inside the lid of a film canister and position three seeds on the towels as described in Experiment 1. Snap the can to the lid, and position it upright, with the lid on the bottom. Check the germination and growth of the seeds daily, until shoots are about three-quarters of an inch (2 cm) tall. This should take about three or four days. Rewet the paper towels as needed.
5. When the shoots have reached the desired height, close the incubation chamber tightly and use the marker or white correction fluid to draw a large arrow on the top of the lid. Orient the chamber horizontally with the arrow pointing up. Secure the chamber to a tabletop or other surface with masking tape. Leave the shoots undisturbed for three to four days, then check the progress. In what direction are the shoots growing?

What's Going On?

Tropisms are growth responses that cause a plant part to curve toward or away from a stimulus. (The word *tropism* comes from the Greek *tropos*, which means "to turn.") In both of these experiments, certain cells in the shoots of the plants elongate, causing growth in a particular direction. The elongation is due to an unequal distribution of the plant hormone *auxin*.

In the *phototropism* experiment, the shoots bend toward the blue window. Receptors in the tip of the developing shoot sense the blue light and cause auxin to be concentrated in the cells farthest away from the light source. Since these cells elongate more than the cells closest to the blue light, the shoot bends toward that light.

When the incubation chamber was oriented vertically in the *gravitropism* experiment, the auxin was distributed evenly in the growing shoot, and so it grew straight up. But when the chamber was turned horizontally, the auxin concentration became greater in the "down" side of the shoot. (See "Plants on the Go," page 16, for additional details.) The auxin causes the cells on the "down" side to elongate, and the shoot bends upward.

The phenomena in both of these experiments are very complex. Experimentally, we've been able to show that plant shoots are attracted to blue light. But as the plant matures and leaves develop, it needs a broader spectrum of light. Try your hand at variations of these experiments and see what develops!

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The *waterfall effect.*

How do we see motion?

This might seem an unusual question. After all, shouldn't seeing something that's moving be the same as seeing something that's standing still? But seeing motion is actually a very special aspect of your visual system, one with important physiological and evolutionary implications.

You don't rely solely on vision to perceive motion, of course—hearing plays an important role, too—but the primary human pathway for perception of motion is visual. The visual system runs on light: Light from the sun or another source bounces from objects into your eye and is focused by the eye's lens onto the *retina*, a membrane at the back of your eyeball that contains millions of light-sensitive cells. The light stimulates some of these cells to fire, and their combined messages are sent to your brain, which creates your visual perception of the world.

So what's so special about seeing things move? Moving objects grab your attention more than almost any other kind of visual stimulus. Like most animals, you've been "hard-wired" by eons of evolution to be especially sensitive to motion. Efficiently detecting a moving object has often meant being able to capture a meal—or avoid becoming one. The evolutionary argument is that animals detecting motion capably were more likely to survive, and the visual adaptations that made seeing motion easier were therefore more likely to be passed on to future generations. This ultimately led to a world populated with animals that were pretty good at seeing motion—like us.

Notice, for example, that you can detect motion virtually *anywhere* in your visual field—unlike fine details, which can only be perceived by looking directly at an object. In fact, while you may be unaware of stationary objects in your visual periphery, they often seem to jump into existence when they move. (See Try This! at left.) In addition, most animals reflexively turn their heads in the direction of motion perceived out of the corner of the eye.

Your nervous system is even adapted to differentiate among different kinds of motion. Specialized cells in your eye and brain react to motion in specific directions. By measuring the visual system's response to lines moving in different directions, researchers have determined that some cells respond only if the lines move in one direction, and other cells respond only to motion in other directions.

Moving objects also present special challenges for the visual system. The image of a moving

by Hugh McDonald

Try This!

Motion makes things visible

Fix your eyes on a point in front of you. Now hold an object (something colorful works well) in your outstretched hand and slowly move it to one side, keeping the object as steady as possible. Stop as soon as you can't see the object anymore, and remember to keep staring straight ahead. Now find out what happens when you move the object up and down.

What's Going On?

Even though you couldn't see the object a moment earlier, it should be visible as soon as it's in motion—demonstrating that you can detect motion at the edge of your peripheral vision.

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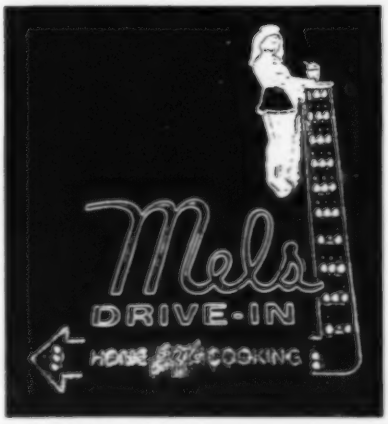
object focused on a stationary retina (when your head and eyes are still) may be identical to the image of a stationary object seen as your head or eyes move. So how does your brain know whether it's the object or your eyes that are moving? Your brain tells these movements apart by analyzing several different kinds of additional information. For example, your nervous system takes the position and motion of your head and eyes into account when it interprets an apparently moving stimulus. Your brain also relies on *vestibular* information to interpret motion: Data from the balance-sensing organs in your inner ear are used to determine where the movement originates. (And under some circumstances, inconsistencies between visual and vestibular information can cause motion sickness; see "That Queasy Feeling" on page 22.)

Along with your sensitivity to motion, though, you're also susceptible to illusions involving motion. We've all experienced these. For example, there's the *waterfall effect*, in which seeing something move in one direction can cause the subsequent illusion of motion in the opposite direction. The name of this illusion comes from a common situation in which it occurs: After keeping your eyes fixed on one point in a waterfall for thirty seconds or so and then looking at a blank wall or rock face, the wall may momentarily appear to crawl upward. As you watch the water, the cells that detect its downward motion adapt and stop responding, and upward-motion detectors then override them for a second or two—so you briefly perceive motion in the direction opposite to that which you first saw.



The *phi phenomenon*.

You may also see motion where there is none. For example, lights on a theater marquee and on some signs can look as if they're moving. That's a special case of the *phi phenomenon*, in which two lights blinking alternately at a certain rate are perceived as one light moving from place to place.

Perceiving motion in a movie is another example of seeing motion where there isn't any. Moving images in film or television are really a series of rapidly flashing still images, but your visual system "holds on" to each image for a fraction of a second (a phenomenon called *persistence of vision*) and combines them to produce the illusion of smooth motion.

The world around us is breathtaking in its complexity, but our visual systems have been shaped by evolution to allow us to perceive the amazing variety of stimuli surrounding us. Seeing provides us with beauty as well as allowing us to detect stimuli important to our survival, and our ability to see and understand motion is an especially fascinating—and challenging—aspect of our ability to navigate our visual world. ➤

Perception Exhibits at the Exploratorium

Vision scientists have found motion to be a particularly rewarding avenue of study, which is why motion perception is a key aspect of the Exploratorium's new *Seeing* collection. The collection showcases contemporary and classic exhibits on vision, many focusing on how we see movement. For example, Silage Beach (by Artist-in-Residence Mowry Baden) puts visitors into a moving environment to generate the strong illusion of physical motion. Depth Spinner gives viewers a taste of the waterfall effect, while Motion Detection and Disappearing Act show how motion can make invisible objects visible. The *Seeing* collection officially opens to the public on June 29, 2002.

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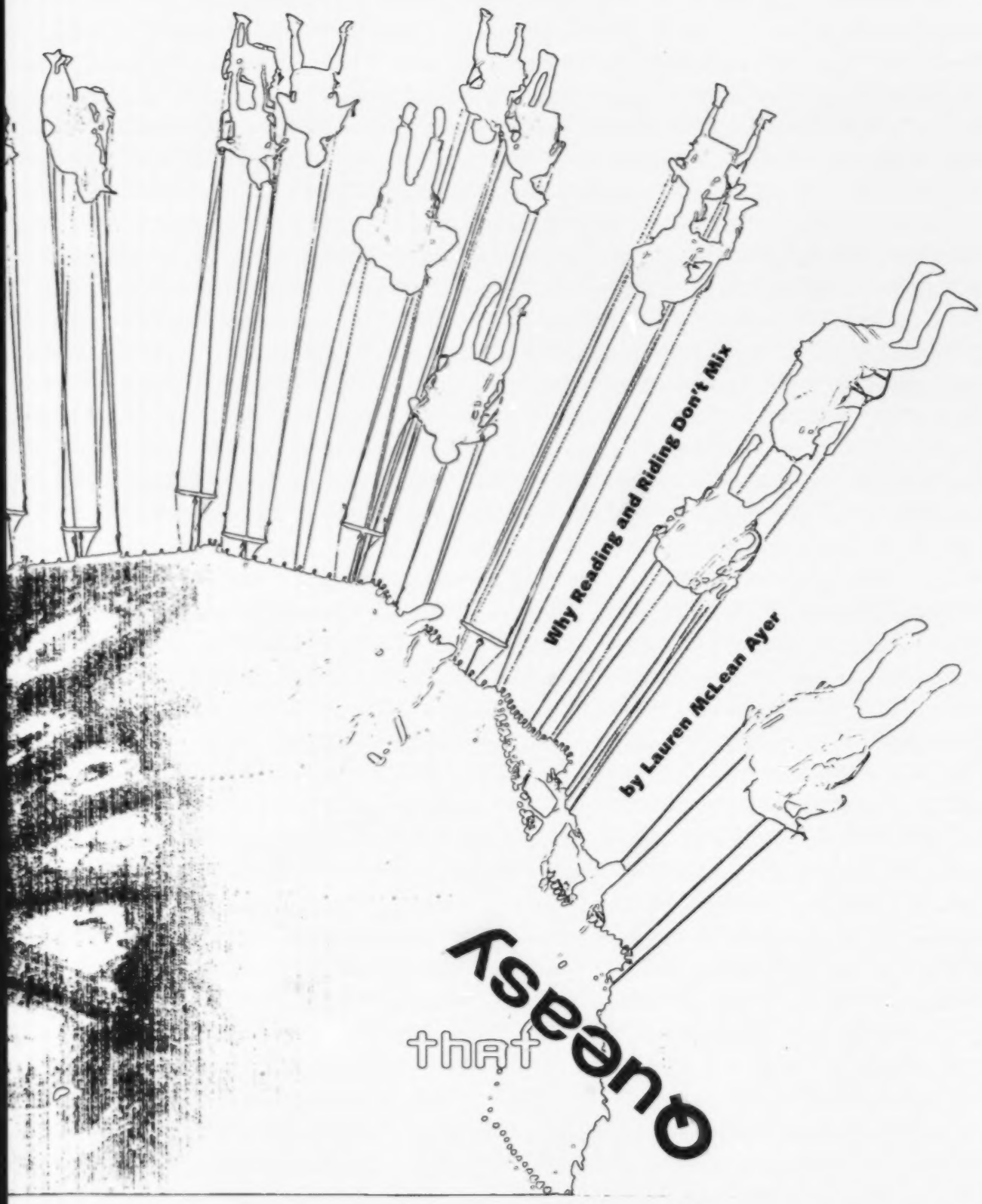

Why Reading and Riding Don't Mix
by Lauren McLean Ayer
Queasy
that

My brother can read in the car. The mere thought of doing that sends my stomach churning. You see, unlike my brother, I tend to get motion sick in anything that moves.

What is motion sickness? Motion sickness is a collection of symptoms resulting from exposure to prolonged or unaccustomed motion. The most common effects include dizziness, nausea, headaches, drowsiness, pallor, and cold sweats. If you have a severe case of motion sickness, you might even pass out.

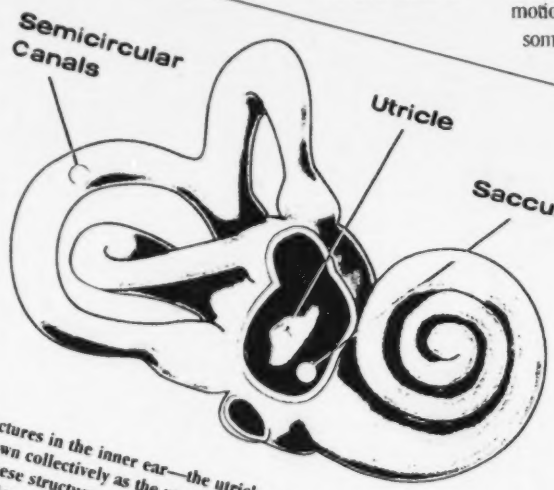
What causes it? Motion sickness commonly results from a discrepancy between what your inner ear senses and what your eye sees.

The inner ear contains several organs, most importantly the semicircular canals, that let you know which way is up, what kind of motion you're experiencing, and whether you're standing still, walking, or tilting your head. Of course, we're exposed to a much wider range of motions than just these. Planes lifting during takeoff, boats pitching in a storm, or the constant rotation of a merry-go-round can all provide unusual input to your inner ear that's likely to disagree with what you see. When your brain receives discrepant information, it doesn't always know how to decode it.

The resulting lack of equilibrium can be mitigated or magnified, depending on what you're doing with your eyes. If you're looking out the window and you're seeing the same kind of motion as that detected by your inner ear, you might not feel sick at all. If, however, you're focused on some stationary object, such as a book, the contradiction between the visual perception of being still and the vestibular (inner ear) perception of movement may create a conflict that can make your symptoms worse.

Why me and not my brother? Some people are just more sensitive. Especially people prone to inner ear disorders including allergies and infections. Children between the ages of two and twelve also tend to be more susceptible because the systems of their inner ears are less mature and have had less time to adapt to unusual kinds of motion.

Your emotional state can also be a factor. If you're nervous about flying, your stomach may be a little on edge to begin with, making it easier for the symptoms to take hold. Illness, especially an upset stomach or headache, can also make you more prone to motion sickness.



Three structures in the inner ear—the utricle, saccule, and semicircular canals, known collectively as the vestibular organs—sense changes in body position. These structures contain hair cells, specialized cells with small hairlike projections that extend into a gelatinous material. Head movements agitate the gelatinous material, which bends the hair cells; different kinds of movements stimulate different hair cells. In turn, the hair cells send very precise information regarding linear acceleration and rotation to the brain.

What can I do? Your best bet is prevention. A couple of simple precautions will usually do the trick. Perhaps the best things you can do to minimize the discrepancy between eye and inner ear are to make sure your seat faces in the direction you're traveling and to look toward the horizon. If you're flying, opt for the seats directly over the wings where you'll feel more stable. On a boat, stay on deck and sit near the center where the boat rocks the least.

It's best not to travel on an empty stomach, which may be more prone to upset. On the other hand, heavy, greasy, or just plain strange foods also tend to make things worse. Save the hot dogs and cotton candy for after your roller coaster ride.

Fresh air can minimize the effects of motion sickness. Crack the window when you're stuck in the car—unless you're behind a semi spewing diesel fumes. That smell can make a person nauseous all by itself. Stopping frequently to get out and walk around a bit can also help keep any impending symptoms from taking hold.

Acupressure has also proved effective. Constant, steady pressure applied to a certain point on the inner wrist can not only keep motion sickness from taking hold, but it can sometimes even stop symptoms once you're already in the throes. Some people find relief by wearing wristbands designed to exert pressure on the exact wrist point, although their usefulness is subject to controversy.

If you've tried all these tricks and you still find yourself getting sick, you may have to rely on medications. Antihistamines are a common choice, because they block input from from your inner ear from reaching your brain. Drowsiness as their most common side effect. Medicate before you leave (usually forty to sixty minutes)—and again along the way if the trip is longer than the duration of the drug. Be sure to take the next dose before the previous one wears off, or you'll be fighting both symptoms and side effects.

Which solution do I prefer? During years of combating motion sickness, I've tried all the tactics mentioned above—with pretty good success. As long as I keep my eyes on the horizon, eat a little something before I get in the car, and keep the windows cracked, I do okay. And by using the acupressure bands, I've even been able to glance at a map without major repercussions. I may never read a book in the car, but that's fine. I prefer to look at the scenery anyway.

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MY PEDAL IS TO THE METAL BUT I CAN'T BREAK 99.9!
S. KEARSLEY

THE ULTIMATE Speed Limit

by Paul Doherty

Three hundred million meters per second. Not just a good idea. It's the law!

We live in slow motion. Slow, that is, compared to the speed of light. The fastest people have ever traveled was on a trip from the earth to the moon; it took three days. Light makes the same trip in one-and-a-half seconds.

In the seventeenth century, Isaac Newton figured out laws of motion that worked for all the objects of his time. Even today, these laws work well for objects moving as fast as trains, planes, and rockets. At the birth of the twentieth century, however, Albert Einstein formulated the special theory of relativity, a new set of laws that give better descriptions of extremely high-speed motion than Newton's laws do.

Einstein's postulates are so far from our everyday experience that they seem like science fiction—yet experiments prove them true. Let me introduce you to a few of the seemingly strange rules that describe the fast motions of small objects with two science fiction stories about a speed-crazed man who finds himself in a very strange place.

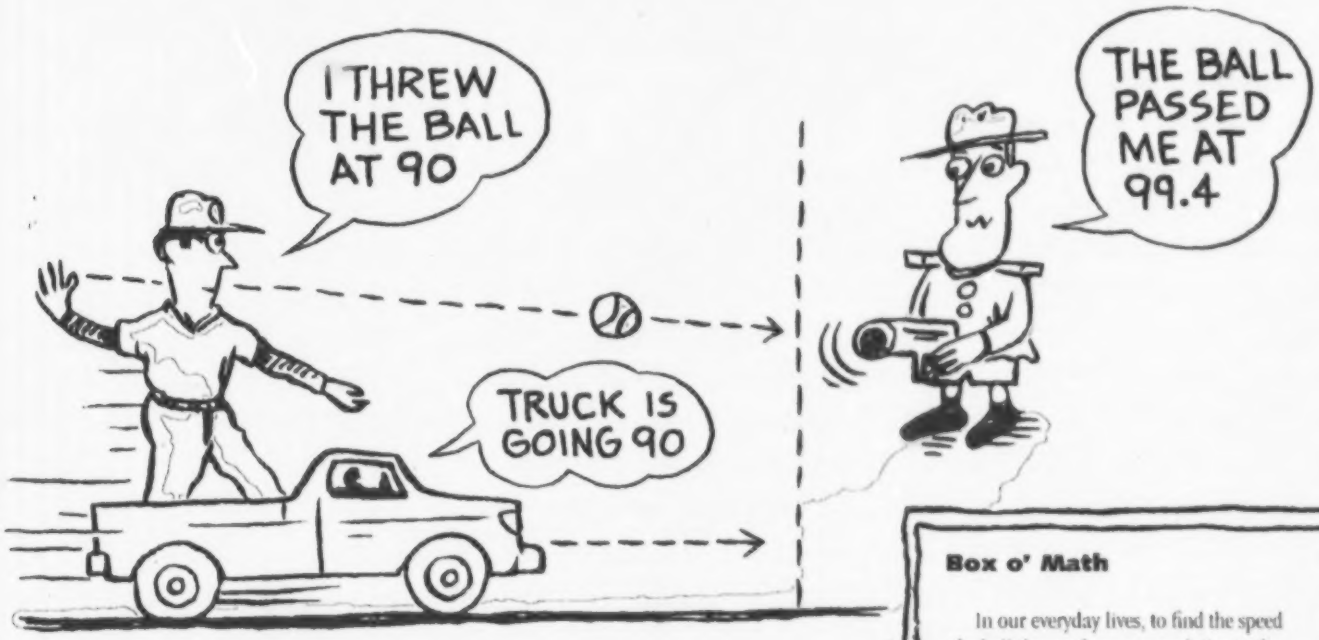
Joe tries to break the speed limit

Joe Speed drove into the land of slow light, a place where the speed of light is 100 kilometers per hour (kph). "That's not so fast," Joe thought. "I'll bet I can easily go faster." He immediately took up the challenge and stomped on the gas. The speedometer dial moved upward, passing quickly from 50 to 80, more slowly from 80 to 90, and then slower still from 90 toward 100. Although he drove for many hours, gradually increasing his speed all the while, he never quite managed to reach 100 kph.

The speed of light seemed just slightly beyond his grasp, so Joe figured that he needed a more powerful vehicle. He went out and bought himself a souped-up muscle car that blew flames from its exhaust. Joe smiled as he pulled onto the expressway and put his pedal to the metal. His head snapped back into the headrest as he went from 0 to 90 in under three seconds. "Now this is more like it," he thought. But, as before, the rate at which his speed was increasing got slower and slower. So although his speed rose toward 100, it never reached it. No matter what he did, he couldn't go as fast as light.

What was going on? Joe ran into a speed limit that was impossible for him to exceed: the speed of light in his universe, 100 kph. In the universe we live in, physicists have found a similar limit, the speed of light in a vacuum: 300,000,000 meters per second, or 186,000 miles per second. Like Joe Speed, no matter how hard we try, we cannot make particles reach or exceed the speed limit—although we've figured out how to make things go pretty fast.

Inside your television, for instance, an electron gun shoots electrons at the phosphor coating on the inside of the picture tube, which becomes excited and gives out the light that you see. The electrons are accelerated from rest to 30 percent of the speed of light in a space that's about the width of a finger. Imagine, then, what scientists can do with an accelerator three kilometers (2 mi) long. California's Stanford Linear Accelerator pushes on electrons even harder than they get pushed in your television, and it pushes them for over two miles. Yet the electrons don't exceed or even match the speed of light, although they get really close, reaching 99.999999995 percent of light's speed. When you push on the electrons they go a little faster, and as they go faster, they act as if they're a lot more massive. By the time they reach the end of the accelerator, they behave as if they were 100,000 times as massive as electrons at rest. The more massive something is, the harder it is to accelerate it. Even if you could capture all the energy in the universe and put it into one electron's motion, you could not make it exceed the speed of light.



Joe attempts to add velocities Although he'd been thwarted in his first attempts to break the speed limit, Joe Speed had a clever idea. He thought he could still succeed with a little help from his friends Sam and Monty and a couple of radar guns. He borrowed a pickup truck that had a maximum speed of 90 kph. He asked Sam, a baseball pitcher, to stand in the back of the truck while it was going full speed and throw a 90-kph fastball in the same direction as the truck was moving. Joe assumed that the speed of the car added to the speed of the ball would be 180 kph and so exceed the 100 kph speed of light. A radar gun in the truck and another outside the truck would collect data and prove Joe's idea right or wrong.

As soon as the truck's speedometer read 90—the speed of the truck over the ground—Joe signaled to Sam, who threw his best fastball. A glance at the speed display of the radar gun in the truck bed showed Joe that the pitch was doing 90 relative to the truck. Then Joe looked ahead to Monty, who was standing at the side of the road with the other radar gun, and was shocked to find that the ball was only going 99.4 kph.

Things got really strange when the sun went down and Joe turned on the truck's headlights. The light traveled at 100, the speed of light relative to the truck. It also traveled at 100 relative to Monty. The light passed Monty doing 100 whether the truck was standing still, moving toward Monty at nearly 100, or even moving away from Monty at 100. Light always travels at the speed of light. In the realm of high speeds, the rule for addition is 1 + 1 = 1, where the speed of light is 1. The speed of light is truly the ultimate speed limit.

What Joe didn't know is that the law of addition of velocities is not the law of addition he learned in first grade. It's a new relativistic law. The new law assures that he can't break the speed of light limit.

In our real world, when we deal with objects shot out of a high-speed explosion like those that take place in particle accelerators, we find that we have to use a different law of addition. If a uranium nucleus is going 90 percent of the speed of light and shoots out a helium nucleus at 90 percent the speed of light, the helium will be going 99.4 percent the speed of light, just like the baseball in Joe's world. The law of addition is given in the Box o' Math on the right.

We experience life in the slow lane of the universe, where everyday rules and everyday arithmetic work just fine. But when we deal with extremely high speeds, we find that these rules are only approximations of the more complex rules of relativity. ➤

Box o' Math

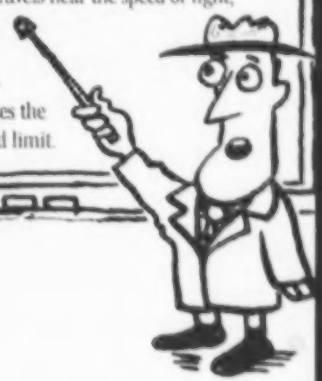
In our everyday lives, to find the speed of a ball thrown from a car relative to the ground, v_t, we add the speed of the car, v_c, to the speed of the ball, v_b:

$$v_t = v_b + v_c$$

At speeds approaching the speed of light, however, we have to apply a new law: We have to divide by a term that grows larger as something goes faster. In this equation, c is the speed limit, the speed of light.

$$v_t = \frac{v_b + v_c}{1 + \frac{v_b v_c}{c^2}}$$

The new equation happens to work just fine with slow-traveling objects, because at low speeds the denominator is approximately equal to 1, and we're right back to our everyday rule for adding velocities. As something travels near the speed of light, however, dividing by the denominator imposes the cosmic speed limit.



Awards Dinner Marks Twenty-Fifth Anniversary

Once a year, leaders in business, science, and education gather at the Exploratorium's Awards Dinner to honor the best in their fields. The event, which marks its twenty-fifth anniversary on May 7, 2002, has long been one of the Exploratorium's most successful fundraising efforts. But beyond the money it raises, the Awards Dinner has also fostered a host of invaluable connections that the Exploratorium can count on for years to come. With the help of these friends, the Exploratorium continues to nurture the kind of curiosity and creativity embodied in the Awards Dinner's honorees.

Ginny Carollo Rubin, the Exploratorium's Director of Development, conceived the event in the hope that it would help develop strategic alliances and a growing network of supporters. "The first Dinner was a relatively modest affair," says Rubin, explaining that the evening, which honored Silicon Valley pioneer Frederick Terman, raised about $10,000. "Since then, it's grown into a major event—a truly stunning evening that raises upwards of $1 million per year."

This year's Awards Dinner is sponsored by Sony Corporation, a longtime collaborator with the Exploratorium in the area of science education. The event will honor biotechnology leaders George Rathmann and Paul Berg, as well as Pulitzer Prize–winning science writer Laurie Garrett.

For many guests, the Awards Dinner provides an introduction to the kind of hands-on learning that has made the Exploratorium famous. And while many come to the dinner for the opportunity to network, the event invariably drives home the importance of supporting science education.

In a speech at the 1997 Awards Dinner honoring Carl Sagan, the astronomer's widow, writer/producer Ann Druyan, called science "the most revolutionary force in the history of the world to demystify, to challenge authority, to democratize."

"The spirit of this place is something he [Sagan] cherished and believed in," she continued, addressing the event's guests, "and I want to congratulate each and every one of you for having the wisdom and the foresight to support this place, because it's very important for the future of our democracy." ➢

Laurie Anderson receives the Art and Technology Award from Goéry Delacôte, 2000.

Honorees 1999 *(left to right)*: Jim Clark, Linda Darling-Hammond, Stephen Jay Gould.

AWARDS DINNER HONOREES

through 2002

2002
Dr. George B. Rathmann
Laurie Garrett
Dr. Paul Berg

2001
Larry W. Sonsini
Brian Greene
Julie Packard

2000
C. Richard Kramlich
Laune Anderson
Paul G. Hewitt
Phyllis Wattis
Nobuyuki Idei

1999
Jim Clark
Stephen Jay Gould
Linda Darling-Hammond

1998
Andrew S. Grove
Heidi B. Hammel
Maxine F. Singer

1997
Alejandro Zaffaroni
Carl Sagan
Bruce Alberts

1996
Edward R. McCracken
Daniel E. Koshland
Shirley Mahaley Malcom

1995
Thomas Perkins
Richard Hart
Dr. Robert Metcalf
Howard Gardner

1994
Gordon E. Moore
David Suzuki
Teresa Trejo-Mejia

1993
David Packard
Walter E. Massey
Phyllis Morrison

1991/1992
Francis Crick, F.R.S.
Don Herbert
Tayeko Kaufman

1990
Harold E. Varmus and
J. Michael Bishop
Wilson Wong

1989
Alan C. Kay
Judith Christensen

1988
Carver Mead
Sidney D. Drell
Donald J. Rathjen

1987
Harold E. Edgerton
The Cousteau Society

1986
Donald C. Johanson

1985
Marian C. Diamond

1984
William R. Hewlett

1983
Robert N. Noyce
Philip Morrison

1982
Carl Djerassi
Lewis Thomas

1981
Henry S. Kaplan

1980
Donald H. McLaughlin

1979
Wolfgang K. H. Panofsky

1978
Russell V. Lee, M.D.

1977
Frederick Emmons Terman
David Perlman

Left to right: Intel cofounders Andy Grove (Honoree 1998) and Gordon Moore (Honoree 1994); Frank Zarb, Chairman and CEO of the National Association of Securities Dealers; Leslie Vadasz, Senior Vice President, Intel; F. Van Kasper of Wells Fargo Van Kasper; C. Richard Kramlich (Honoree 2000), Partner, New Enterprise Associates.

Honorees 1983: The late Robert Noyce *(left)* and Philip Morrison.

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Reviews & Resources

Notes for *Moving Pictures...* (page 13)

a. I shot this image with a "point-and shoot" pocket camera (Yashica T4).

b. I used a Mamiya RB67, a medium-format camera. (Medium-format cameras allow for larger negatives [6 cm × 7 cm instead of 35 mm]). I did a series of exposures on the same frame of film, firing a strobe with each movement. A switch on the back of the camera allows me to repeat the same frame many times. You can achieve the same effect with any 35-mm camera by manually rewinding the camera one full turn after each shot.

c. I set up a small bed in the studio, with a Hasselblad 503CW (medium-format) camera on a tripod pointing directly over the bed. I used a small Maglite as the light source, holding it at a slight angle to the woman's face. I photographed four positions, each held for 15–20 seconds. You can also use any 35-mm camera with the shutter set on "B" (for "bulb"), which allows you to vary exposure time by holding down the shutter button for any length of time. All four exposures were done on the same frame of film, using the technique explained in photo b.

d. I took this in my studio with two sets of stairs and two strobe lights: one to light the front of the stairs and one to light the side. I synched my 35-mm camera (Nikon F100), which has a built-in motor drive, to the strobes. These fired at a speed of 1/125th a second. By rapidly firing shots as the woman climbed the stairs, I was able to get a sequence of movements.

e. I shot this with a Hasselblad 503CW, 160ASA film (a slower-speed film), and a small Maglite, first removing the face cap, lens, and reflector to reveal the bare bulb. I set up my camera on a tripod pointing straight upward, and threaded fishing line through the top of the flashlight. I then dangled the flashlight from a pole and pushed it to set it in motion. For each photograph, I opened the shutter for 30–60 seconds. A 35-mm camera with the shutter set on "B" (see note to photo c) works, too.

f. I shot this in my darkroom using a Mamiya RB67 and a flashlight. I took several 10-second exposures, all on the same frame of film, over the course of 3 or 4 hours. Instead of using a timer, I went into the darkroom periodically to snap the photos. You can also do this using a 35-mm camera and the same technique for multiple images on one frame as described in photo b.

g. I captured the spiral movement of dry ice floating on water in a bowl using a Hasselblad 503CW set at a very high shutter speed (1/500th of a second), and placed two flashlights at almost the same level as the water for the light source. Any 35-mm camera with the shutter set on "B" will work too (see note to photo c).

Tools & Toys

I think I was a whirling dervish in a former life. When I was a child, one of my favorite things to do was spin. My dad has many home movies in which I am captured for posterity, twirling like a propeller on a beanie. (Too bad if any of my siblings were in the way!) I loved the dizzy, disoriented feeling I experienced as a result of spinning around and around like a maniac.

My carefree days as a human whirligig soon ended, however. The older I got, the less tolerant I became of any motion (other than straight forward). Nowadays, just going through the turnstile at the grocery store can make me queasy. I can still spin vicariously, though, while watching the wind-up whirler, **Spinney ($10.90)**. Just turn a key and this crazy nuts-and-bolts contraption spins and bounces with frantic abandon, resembling nothing so much as a tiny Kentucky Derby contender with an inner-ear imbalance. Spinney's companions in kinetic craziness, **Cranky ($10.90)** and **Sparklz ($13.90)**, also move in ways unique to their kooky

Sparklz

structures. **Cranky** holds photos or business cards in his tin antennae while dancing and hopping about, and **Sparklz** speeds lopsidedly along while creating miniature lightning bolts on its turntable tummy. A nice addition to the mix of this turbulent trio are **Tetra Tops ($9.90/$11.90)**. You would never believe these small mounds of marbles, glued together into asymmetric pyramids, could spin, but they do, and for a surprisingly long time. A skillful flick of the wrist and *voilà!* Tetrahedrons, octahedrons, icosahedrons, and cuboctahedrons are propelled into polyhedral polkas.

Watching these marvelous gadgets expend so much energy can be quite exhausting, however, and so I have to seek a quiet spot where I can regain my strength. Simple person that I am, I am happy lying on the couch for hours, just staring into space. But a great deal more interesting and mind expanding is to watch the perpetual motion of **Jupiter ($14.50)**. Much less spastic than Spinney et al., the circling orbs of this mini universe-in-motion serve to soothe my spirit and captivate my mind as I follow the intricacies of its constant movement. Equally enthralling is **Levitron ($65.90)**. Like a miniature flying saucer, this sophisticated top hovers and spins on magnetic waves above a miniature space-age platform, mesmerizing me with its ability to levitate, reminding me of the days when I myself could spin so unencumbered, so fast and free.

Observing all of this movement around me is very inspiring. Perhaps it will shake me out of my tendency toward dormancy and propel me to seek adventure. I only wish I could still stomach the sensation of whirling like a dervish and spin myself into discovering deep secrets of the cosmos. Who knows, maybe I'd receive some divine inspiration for, say, how to make washing the dishes over and over and over and over again into an exciting, fulfilling experience rather than the nexus to a nervous breakdown.

—Martha N. Steele

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Related Reading

Plants on the Go by Katharine Miller

Roger Hangarter at Indiana University has created a Web site, "Plants in Motion," an online source of time-lapse plant movies, including movies showing phototropism and response to blue light: http://sunflowerbio.indiana.edu/~rhangart/plantmotion/PlantsInMotion.html

Cosmic Collisions by Robert Irion

One Universe: At Home in the Cosmos by Neil deGrasse Tyson, Charles Liu, and Robert Irion. Washington, DC: Joseph Henry Press, 2000. This large-format, award-winning book, cowritten by the author of this article, features an extensive section on the physics of motion in the universe, with many explanatory illustrations and astronomical photographs.

The Paths of Paths by Steven Vogel

Prime Mover: A Natural History of Muscle by Steven Vogel. New York: W.W. Norton & Company, Inc., 2002. This work is a thorough and engaging account of how muscles work and how their physiology has influenced the development of human culture.

Motion in the Eye of the Beholder by Hugh McDonald

For general information about visual perception, here are two good Web sites:
http://www.psc.edu/science/Miikkulainen/Miikkul.html
http://webexhibits.org/causesofcolor/index.html
This Web site provides a fascinating account about a woman who has lost her ability to see motion:
http://www.hhmi.org/senses/b210.html

Moving Pictures... by Amy Snyder

Photography by Barbara London (editor) and John Upton (contributor). New York: Addison-Wesley Publishing Company, 1997.
This work offers an all-inclusive look at the craft of photography, with detailed coverage of the major specialties and techniques.

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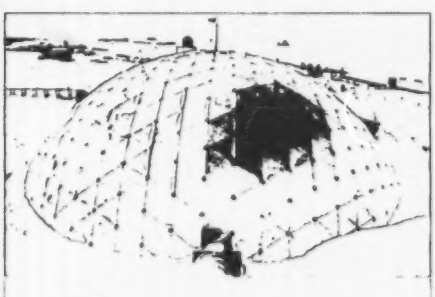

Next: Special Expedition Issue

Exploratorium staff members recently had the rare and exciting opportunity of visiting scientific research stations in Antarctica. In our next issue, our intrepid explorers will tell you why scientists from many different fields are working in Antarctica's extreme environment—and what they're learning.

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